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# A spatially distributed analysis of erosion susceptibility and sediment yield in a river basin by means of geomorphic parameters and regression relationships

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## Abstract

In the present work, an application of statistical regression relationships utilising geomorphic parameters is attempted in a spatially distributed mode, in order to predict the amount of river sediment supply at varying sections of the drainage network. Simple and multiple regression relationships utilising drainage density $D_d$ and hierarchical anomaly index $\Delta_a$ as independent variables were applied to the Calvano watershed (Central Italy) at different degree of subdivision in tributary drainage basins, so as to assess their contribution to the whole watershed sediment yield balance. In the same way, the role of small hill-reservoirs as sediment-trap and that of areas affected by badlands and of tributary basins exposure were also investigated. Results were tested on the basis of sedimentation estimates from selected reservoirs. The relationships provided a yearly specific sediment yield (SSY) value for the Calvano stream which is according to the average observed SSY in river basins of central Italy flowing to the Adriatic Sea.

The use of simple statistical relationships, such as those here adopted, can allow to recognise the sections along the main stream which are more critical in terms of sediment accumulation, which, on turn, can cause sudden water discharge increments and dangerous floods. This approach can provide a tool enabling to locate the hydraulic risk and to point out the areas where soil conservation practices or hydraulic works, such as periodic maintenance of riverbeds, are needed in order to reduce soil erosion and sediment accumulation.

## 1 Introduction

Understanding geodynamical processes like sediment production by water erosion and river sediment transport plays an important role in the fluvial-system management. This is due to the side-effects these processes can produce, such as reduction of soil production capacity, reservoirs siltation, variations and instability of channel beds and river banks and so forth. Moreover, sediment moving from slopes to drainage network can be deposited along the streams: this accumulation can cause dangerous overflooding when exceptional water discharge after heavy rainstorms reaches the silted river. To be able to forecast these processes is therefore a binding requirement in land management, which must be satisfied by adopting suitable tools allowing to evaluate the related risk.

When data records are lacking, estimation models have to be utilised. With the aim to predict sediment production and transport, since many years to date, researchers have tried to give an answer by means of different approaches, from empirical to physically based hydraulic models, taking into account different physical laws and parameters. To this aim, Kirkby and Cox (1995) pointed out that hydrologic processes responsible for rill formation seem to be prominent at the detailed scale; while topographic, pedologic and vegetation factors begin to prevail at the basin scale, which represents a local planning level; last, factors linked to climate and lithology take relevance at the regional and global scales, which constitute the national and over-national planning level. In addition, another aspect must be taken into account, namely, model suitability in terms of economic costs (balance cost/benefit) and data efficiency. Physical models often reveal to be expensive and very time-consuming when applied on a land planning and management scale. Also empirical models like the Universal Soil Loss Equation (USLE), successfully applied in many parts of the world, can become unpractical, in some circumstances, mainly because of the need to support field surveys aimed to gather soil data (K-factor) over an extended area and the frequent unavailability of complete rainfall records allowing to calculate the rain erosivity R-factor.For these reasons, the geomorphic approach, based on simple cartographic data, assumes relevance as useful management tool, since it can meet both the requirements of reliability and ease of employment needed for planning and assessment purposes (Lupia Palmieri, 1983).

Since the 1950's–1960's up to recent years, several authors have shown the effectiveness of regression relationships which correlate river sediment transport with easily available geomorphological, hydrological and climatic parameters (Anderson, 1957; Langbein and Schumm, 1958; Fournier, 1960, 1969; Douglas, 1968; Cooke and Doornkamp, 1974; Capozza, 1963; Gazzolo and Bassi, 1961, 1964; Cavazza, 1972; Ciccacci et al., 1977, 1980; Cannarozzo and Ferro, 1985, 1986; Ichim and Radoane, 1987). Another interesting correlation was suggested by Copertino et al. (1977), who hypothesised a link between geomorphic parameters and fluvial hydraulic regime, in order to predict flood events. According to these studies, a causal link would exist between flood self-regulation capacity and network organisation. This capacity will lower with basin area, due to the reduction of the total length and of the frequency of main order streams, which implies the reduction of the average section of riverbeds. Mainly in small catchments, the hydro-meteorological factors alone (runoff coefficient, rainfall, permeability etc.) cannot be enough to represent all the factors involved in the flood formation. Therefore, the Authors also considered other factors, such as those related to basin and drainage network characteristics, which can play a role in determining the flood probability.

In the present work, regression relationships utilising geomorphic parameters are applied within a watershed in a spatially distributed mode, that is, at different degree of subdivision in tributary drainage basins, in order to predict the amount of river sediment supply at varying sections of the drainage network, which can be critical in terms of sediment accumulation along the streams and of related hydraulic risk.

## 2 Study area

The study refers to the Calvano stream watershed, located in the Abruzzo Region (central-eastern Italy). This area is representative of the typical geomorphological and geohydrologic conditions of the piedmont belt comprised between the turbidite-limestone Appennines ridge and the Adriatic Sea (Fig. 1).

The Calvano stream watershed is cut on pelagic sediments and continental eroded materials of middle Pliocene-lower Pleistocene age (the Mutignano Formation). Clays are prevalent ("Blue Clays") with intercalated conglomerates and sands (Fig. 2). The hilltop deposits form tabular bodies, gently dipping towards ENE, constituted by sands and conglomerates from marine-transitional to continental environment, deposited during the regional uplift which brought to the total emersion of the area between lower- and middle-Pleistocene. The stratigraphic setting is almost homogeneous in the whole area, which can be described as a wide monocline, 5°–8° dipping and directed about N 180°. The characteristics of the Calvano stream watershed are common to most of the river basins in the whole peri-Adriatic belt of Central Italy. The typical morphology is given by hilly ridges and fluvial valleys, almost oriented SW-NE, modelled on sandy-clay terrains and subject to severe erosive processes. In the examined river basin, one main ridge and two secondary sub-parallel ridges are distinguished, dividing the catchment area into three belts. Starting from the sea-mouth, the elevations progressively grow from north to south and from east to west up to 461 m a.s.l., at the south-western edge of the basin. The overall morphology and the superficial hydrography are influenced by recent tectonics which produced a series of differential uplifted blocks. Three main fault-systems can be recognised (Nisio et al., 1997; Parea and Valloni, 1983): the first, almost directed W-E, strongly controls the main stream course and cuts the secondary fault-systems; the second is directed SW-NE and drives the secondary hydrographic network, while the third is parallel to the coast-line, directed SE-NW, and influences the minor drainage network.

According to Strahler's classification, the Calvano stream basin is ranked as 5th order. Its fluvial network shows a sub-dendritic pattern, with main tributary watercourses embedded in narrow valleys. The main alluvial plain is very limited in dimensions as it extends few kilometres from the confluence between the two main tributaries (Fosso Reilla and Fosso di Casoli) to the sea-mouth. There are no water discharge nor sediment yield gauging stations along the watercourse. Slopes sharply decrease in correspondence of the main stream. The hydrographic network is mostly developed in the hilly most-elevated part of the watershed, where well developed, somewhere spectacular, badlands systems (*calanchi*) occur, prevailingly on south-facing slopes. In this situation, a significant percentage of sediments supplied by the mountain streams is expected to be deposited in the main course.

The general hydro-geomorphological setting determines a hydraulic risk for the human settlements down-valley, around the city of Pineto, located on the river mouth. In fact, the area is subject both to floods and slope-instability. The last severe flood occurred in July 1999 when the coastal plain was submerged by waters, with heavy damages to structures, roads, buildings and a high number of evacuees (CNR, 1993). The triggering factor was recognised in the river-bed overflooding due to the huge detrital supply along the main stream from the secondary channels network, which is determined by the low bedrock permeability, the short catchment length, the high tributary slopes steepness and the fine textural dimensions of transported sediments.

The climate is Mediterranean-type, with long dry summers and rainfalls concentrated in winter periods (average yearly rainfall: 750 mm). This regime induces prolonged soil aridity and superficial soil cracks, mainly on clay south-facing slopes, which heavily affect slope-stability and soil erosion vulnerability. In the same time, the low soil-permeability favours superficial runoff which can produce dangerous floods after heavy rainstorms.

Land-use is characterised by intense urbanisation along the coast and by scattered farms in the inner hilly zone. The hilly area is cultivated, mainly with arables, while olives and vineyards are more limited. The frequent practice of inappropriate cultivation techniques, such as up and down tillage along the slopes, triggers rill/gully erosion and mudflow processes. These processes, on turns, can develop towards more severe erosion forms such as large mass movements and badlands on sandy-clay slopes (Vittorini, 1977; Ballerini et al., 1992). Nowadays, many cultivated fields are going under abandonment and the natural vegetation is beginning to re-colonize the area.

Another characteristic treat of the local landscape is represented by numerous small hill-reservoirs which are spread throughout the area, associated to agricultural activities for irrigation purposes. Their occurrence witnesses the impermeable nature of soils and bedrock and the poor water availability.

## 3 Framework of the analysis

### 3.1 Regression relationships

Ciccacci et al. (1987) investigated the correlation between the yearly specific sediment yield per unit area (SSY) and some geomorphological, hydrological and climatic parameters from 20 watersheds distributed along the Italian peninsula. On that basis, they developed some multiple regression relationships where the main independent variable was the drainage density $D_d$, used alone or associated with, respectively, the hierarchical anomaly index $\Delta_a$, the mean annual river discharge Q ($m^3/s$), the Fournier's Climatic Index and a climatic parameter introduced by Ciccacci et al. (1977), given by the total amount of yearly rainfall, P, multiplied by the standard deviation of monthly rainfalls.

Let us denote with $G_a$ the number of 1st order streams necessary to make a drainage network perfectly ordered in a binary tree-shaped structure with streams of order $u$ flowing into streams of order $u+1$, with $N_1$ the number of 1st order channels actually occurring in the drainage network and with p the rainfall in the wettest month. Then, the hierarchical anomaly index $\Delta_a$ is given by the ratio $G_a/N_1$, while the Fournier's Climatic Index is given by $p^2/P$.

The regression relationships studied by Ciccacci et al. (1987) showed a high coefficient of determination (the best $r^2$ value was 0.96, with drainage density and hierarchical anomaly index as independent variables) and an average percentage error between observed and predicted data of 13–14%. Ciccacci et al. (1987) deemed drainage density $D_d$ as the most significant parameter when estimating SSY, as it can resume in itself the overall climatic, vegetation and geological conditions whose combination results in watershed erodibility potential. Moreover, considering that river transport processes are influenced by the physical characteristics of watershed as well as by the drainage network topology, a parameter such as hierarchical anomaly index $\Delta_a$ can account for the drainage network organisation.

Subsequent statistical analyses have revealed that the correlation between the drainage density and SSY is not always as significant (Cannarozzo and Ferro, 1988; Grauso et al., 2007[1]). However, in any case the role played by the drainage density on the soil erosion susceptibility has relevant implications from a technical point of view. In fact, geomorphic parameters can be estimated from maps or remote sensing observations while river discharge and rainfall data are generally not available for ungauged basins (Sivapalan et al., 2003). Furthermore, relationships with geomorphic parameters are recommended to be used when predicting the potential sediment supply from small scale tributary basins. In fact, in these particular cases, river discharge records are generally lacking, and a climatic index, which is currently obtained from a raingauge stations network, cannot be defined at a spatial scale fine enough in order to detail the local conditions for small scale river streams. Conversely, the geomorphic parameters can be effectively downscaled on the basis of a detailed representation of the basin elevation.

In the present study, the following logarithmic relations, developed by Ciccacci et al. (1987), which have already been employed in several other studies in Italy (Ciccacci et al., 1988; Battista et al., 1988; Lupia Palmieri et al., 1995; Agnesi et al., 1996; Massaro et al., 1996; Ceci et al., 1998), are utilised:

$$\log \mathrm{SSY} = 0.3262 Dd + 0.1025 \Delta a + 1.4478 \qquad (1a)$$
$$r^2 = 0.96$$

$$\log \mathrm{SSY} = 2.7969 \log Dd + 0.1399 \Delta a + 1.0595 \qquad (1b)$$
$$r^2 = 0.96$$

$$\log \mathrm{SSY} = 0.3371 Dd + 1.5239 \qquad (2a)$$
$$r^2 = 0.96$$

[1] Grauso S., Pagano A., Fattoruso G., De Bonis P., Onori F., Regina P., and Tebano C.: Relations between climatic-geomorphological parameters and sediment yield in a Mediterranean semi-arid area (Sicily, southern Italy), Environ. Geol., Sprinter-Verlag ed., under revision, 2007.

$$\log \mathrm{SSY} = 2.9394 \log Dd + 1.1343 \tag{2b}$$
$$r^2 = 0.95$$

The multiple regression (1a) is here applied in most of the 4th and 3rd order tributary basins, while the simple regression (2a) using the $D_d$ alone is utilised when $\Delta_a$ is equal to zero, mostly in catchments only consisting in 1st order and 2nd order streams. In these conditions, hierarchic anomaly parameters have no significance, considering that anomalies arise when 1st order streams flow into 3rd order and higher or 2nd orders into 4th etc..

In a previous work, Ciccacci et al. (1980) observed that, beyond a certain drainage density value, which they established in 6, SSY does not grow exponentially with the $D_d$. Therefore, in the cases with drainage density major than 6, the bi-logaritmic relationships are here utilised (1b or 2b), in order to avoid too high estimated SSY values.

### 3.2 Quantitative geomorphic analysis and river network acquisition

Geomorphic parameters $D_d$ and $\Delta_a$ were obtained by means of the Quantitative Geomorphic Analysis of river network. This methodology allows an objective watershed characterisation and a quantitative comparison among different river basins (Horton, 1945; Strahler, 1957; Avena et al., 1967; Avena and Lupia Palmieri, 1969). The geomorphic parameters calculation was performed by means of the GIS tool Geomorf_2k5, which is the up-to-date version of Geomorf_2k1 (De Bonis et al., 2002). Geomorf_2k5 is an extension of ESRI ArcView®GIS 3.2a which adds to the user interface a set of tools for computing Strahler's stream order and other geomorphic parameters via spatial algorithms. It also contains functions for removing several geometric and topological inconsistencies in the river network layer by editing errors (Fattoruso, 2005).

The Geomorf_2k5 input data were the vector drainage network layer, drawn from official maps, and the vector watershed layers, extracted from a digital elevation model (DEM). The permanent streams (blue-lines) of the drainage network were mapped according to the 1:25 000 topographic maps of the Italian Military Geographic Institute

(IGMI). Then they were integrated by additional information derived from other cartographic sources (Regione Abruzzo, 1982; 1990) at the same detail scale or more (1:25 000–1:10 000), aerial photographs and field observations. Mapping hydrographical data from cartography introduced some geometric and topological inconsistencies. They were removed automatically by means of the Geomorf_2k5 editing functionalities. Watersheds limits were extracted from a high resolution (20m) DEM using several GIS algorithms.

### 3.3 Basin subdivision

In order to evaluate the spatial distribution of soil erosion and sediment yield potential at different basin sections and morphologies, different subdivisions in minor order tributary basins were adopted (Fig. 3). The first subdivision groups the 4th order "partial" catchments (Table 1), to evaluate the gross sediment supply to the Calvano main stream: here, four partial catchments are distinguished (Cascianella, S. Patrizio, Reilla and Sabbione) flowing into the main stream. The remaining main stream valley (5th order) is also treated as partial catchment to investigate its sediment supply potential to the whole basin.

The second subdivision is extended to the 3rd order "sub-catchments": seventeen sub-catchments can be recognised, within the main stream and the four partial basins (Table 2).

Another subdivision was performed by taking into account the "secondary" catchments down to the 1st- and 2nd order, which are drained by small hill-reservoirs (Table 3), in order to evaluate their role in sediment sequestration to the whole sediment yield balance.

A further distinction was made with regard to secondary catchments affected by badlands (Fig. 4 and Table 4), with the aim to assess the relative significance of such severe erosion forms on the whole basin sediment balance.

## 3.4 Test catchments

Four test catchments were selected, with the aim to test the model equations reliability on the basis of reservoir sedimentation estimates, available from surveys carried out by the local public administration or from personal communications by reservoirs owners and designers. It is well known that to validate the results provided by soil erosion models is not an easy task. Therefore, the availability of several test reservoirs located in a small scale basin makes the Calvano watershed an ideal case study for the methodology herein proposed.

Actually, these estimates of reservoir siltation were derived from soft information about the initial and current storage volume of the reservoirs. Therefore these data are affected by some uncertainty, as a direct measurement was not performed. Nevertheless they allow to carry out a meaningful and spatially distributed evaluation of the model performances, as for a catchment which is subjected to a significant soil erosion.

Two test reservoirs are located within the Calvano stream watershed. The first, named 20-Pineto, was built in 1959 and is located in the higher part of the Sabbione sub-catchment. Its drainage area is 0.77 $km^2$. The reservoir storage was computed by the local administration in 1974, which estimated a residual storage capacity of 30 000 $m^3$ instead of the initial 35 000 $m^3$. Then, considering the time-interval of 15 years from the construction, an average yearly sedimentation rate of about 333 $m^3$ can be inferred, corresponding to a specific sediment supply of 4.33 $m^3\,ha^{-1}\,year^{-1}$.

The second test-reservoir, named 119-Atri, is located at the outlet of a 3rd order main stream tributary with a drainage area of 0.98 $km^2$. It was built in 1970 with an initial storage capacity of 70 000 $m^3$. After 35 years, a sediment volume of about 12 500 $m^3$ was estimated (personal communication by owners), corresponding to a sedimentation rate of 357.14 $m^3\,year^{-1}$.

The other two test-reservoirs, 147-Atri and 141-Atri, are located within two neighbouring stream basins (Piomba and Cerrano streams) showing the same geomorphological characteristics of the Calvano stream watershed. Both reservoirs have a drainage area of 0.15 $km^2$. Sedimentation data have outcome from dredging projects aimed to restore the reservoir water capacity. In the first case, a sediment volume of 15 000 $m^3$ was removed after 25 years, corresponding to a sedimentation rate of 600 $m^3$ $year^{-1}$, while, in the second, a volume of 1600 $m^3$ was dredged after 22 years, corresponding to a sedimentation rate of 69.57 $m^3$ $year^{-1}$.

## 4 Results and discussion

Tables from 1 to 4 show the results of sediment yield estimates by means of the equations 1a–1b and 2a–2b. For each catchment, the estimated yearly area-specific sediment yield SSY (Mg $km^{-2}$ $year^{-1}$) and yearly total sediment yield SY (Mg $year^{-1}$) are reported.

The specific sediment yield of the Calvano stream was evaluated in 792.50 Mg $km^{-2}$ $year^{-1}$, which is very close to the average observed SSY in river basins of central Italy flowing to the Adriatic Sea. More likely, this value would appear underestimated, if one considers the dominant high-erodible sandy-clay composition of bedrock in the Calvano stream watershed. In fact, in the same Adriatic sector, SSY values up to 1600 Mg $km^{-2}$ $year^{-1}$and more can be observed in long-period records of river basins where clay formations are prevalent (Lupia Palmieri, 1983). If the Calvano 3rd order sub-basins are analysed, the magnitude of predicted SSY confirms the consistency with lithology (Table 2). In fact, a mean value of about 12 000 Mg $km^{-2}$ $year^{-1}$ is showed.

The first level of basin subdivision (4th order) shows that the S. Patrizio stream can provide the highest sediment supply within the whole basin (about 12 000 Mg $year^{-1}$), followed by the Sabbione stream (about 4700 Mg $year^{-1}$). Moreover, considering that the S. Patrizio outlet coincides with the confluence with the Cascianella partial basin, providing some less than 4000 Mg $year^{-1}$, this point of the drainage network can appear critical in terms of risk of flooding. The same situation can also be observed at the second subdivision level (3rd order sub-basins), where the relative tributary supplies to the main streams can be quantified.

It can be remarked that the sediment supply referred to the whole basin is lower than the sum of its partial basin sediment yields. This can also be verified in the other basin subdivisions down to 3rd and 2nd orders and it is mainly explained by the different entity of drainage density. For example, when referred to the entire Calvano basin area ($D_d$ = 4.05), drainage density results lower than the average $D_d$ of its partial basins (4.99). This produces a sediment yield loss quantifiable in 12% of the expected balance given by the sum of the four partial basins plus the main valley partial basin sediment supply (Table 1). This is in accordance with the assumption that a percentage of sediments moving from tributary basins is re-deposited along the main stream, and it would prove an inherent property, by the adopted methodology, to take into account this process.

Table 3 allows to evaluate the role of small hill-reservoirs in the Calvano sediment balance. In the examined area, 30 small reservoirs occur, located throughout the basin except the Cascianella and S. Patrizio partial basins which are characterised by very steeping slopes and where badlands are widely represented (Fig. 4). The overall area drained by reservoirs (8.32 $km^2$) is corresponding to about 24% of whole Calvano basin area. The outcomes of SSY estimates by the model equations show relatively low values (905.43 Mg $km^{-2}$ $year^{-1}$, on average), considering the bedrock type and according with the need to prevent the rapid reservoirs filling. Despite that, reservoirs as a whole would capture about 4500 Mg $year^{-1}$, meaning that 16% of the Calvano yearly sediment yield is subtracted to the whole sediment balance. This sediment-trap function, together with their widespread distribution, marks the potential by hill-reservoirs as effective hydraulic regulator in the examined area.

With regard to the influence of badlands on sediment production rate, Table 4 clearly show the meaningful role of these areas. Badlands affect the whole area of Cascianella and S. Patrizio and a large portion of Reilla and Sabbione partial catchments. The total surface affected by badlands amounts to 14.64 $km^2$, corresponding to 42% of the whole Calvano area. The estimated potential sediment supply from these areas constitutes 96% of the total basin SY balance. This means that the gross part of the solid supply to the Calvano main stream is produced in these areas and it is delivered at their outlets.

The model equations were also applied to the small catchments draining into the selected test reservoirs. The comparison between the sediment volumes estimates, converted into sediment yield, and the predicted SSY data allowed to test the model equations reliability (Table 5). In absence of direct geotechnical measurements, the reservoir sediment volume data were converted into dry weight units and corresponding specific sediment yields by considering a hypothetical dry bulk density of 1.2 $Mg\,m^{-3}$, which is a suitable value for low-compaction sandy-clay materials. As it can be seen, in the four examined cases, predicted SSYs show an average difference of 36.5% if they are compared with reservoir sedimentation data, the best result being showed by 20-Pineto reservoir catchment (9%), while 119-Atri and 141-Atri show major differences. The comparison provides dimensionally consistent and encouraging results, even if they are based on soft data, as direct measurements were not available, and therefore the estimates of sediment volumes settled inside the reservoirs and theoretical bulk density are affected by significant uncertainty. This procedure gives a suggestion for a suitable erosion monitoring system to be adopted, based on periodic sedimentation surveys on the small irrigation hill-reservoirs which are widely diffused in the examined area.

A last consideration concerns the relations between sediment yield and basin exposure. A real statistic analysis was not made. However, if one grouped the examined secondary catchments into southward and northward facing catchments (Table 6), the considered catchments would be equally distributed in the two groups. The estimated SSY from southward catchments resulted, on average, about three times higher than that from northward catchments, confirming the influence of slope aspect on sediment supply potential.

## 5 Conclusions

Multiple and simple regression relationships to estimate river sediment yield were applied in a spatially distributed mode, with the aim to assess the river sediment supply at



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different sections of the examined river basin. The obtained estimate of sediment yield have been compared with field data of reservoir siltation, therefore allowing a validation of the proposed method.

The order of magnitude of the obtained results of spatial distribution of erosion rates and sediment delivery can be considered reliable. In fact, the relationships provided a yearly specific sediment yield (SSY) for the Calvano stream which matches the average observed SSY in river basins of central Italy flowing to the Adriatic Sea.

The sediment supply from badlands catchments was also evaluated, confirming the very high contribution of these areas to the whole watershed sediment balance. The sediment yield distribution related to the slopes aspect, confirmed the higher susceptibility to erosion and sediment supply of south-facing slopes than differently oriented slopes.

Using simple statistical relationships, such as those here adopted, one is allowed to recognise the river cross sections along the main stream which are more critical in terms of sediment accumulation which, on turn, can cause sudden water discharge increments and dangerous floods. This approach can provide a tool enabling to easily locate the hydraulic risk and to point out the areas where soil conservation practices or hydraulic works, such as periodic maintenance of riverbeds, are needed in order to reduce soil erosion and sediment accumulation.

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**Table 1.** Sediment yield estimates in 4th order partial catchments and the whole Calvano stream basin.

| Partial catchments | Area km$^2$ | Order | Dd km$^{-1}$ | Δa | log SSY | model equation | SSY MG km$^{-2}$ year$^{-1}$ | total SY MG year$^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| Cascianella | 1.48 | 4 | 6.45 | 0.76 | 3.43 | 1.b | 2691.90 | 3984.02 |
| S. Patrizio | 2.69 | 4 | 7.51 | 0.96 | 3.64 | 1.b | 4393.87 | 11 819.51 |
| Reilla | 8.89 | 4 | 3.43 | 0.61 | 2.63 | 1.a | 425.73 | 3784.78 |
| Sabbione | 7.16 | 4 | 4.09 | 0.36 | 2.82 | 1.a | 658.88 | 4717.58 |
| | | | | | | | subtotal | 24 305.88 |
| Main stream partial catchment | 14.63 | 5 | 3.47 | 1 | 2.68 | 1.a | 481.00 | 7037.10 |
| | | | | | | | subtotal | 31 342.98 |
| CALVANO whole basin | 34.85 | 5 | 4.05 | 1.27 | 2.90 | 1.a | 792.51 | 27619.08 |
| | | | | | | | SY loss from the total balance = | 12% |

**Table 2.** Sediment yield estimates in 3rd order sub-catchments.

| Sub-catchments | Area km$^2$ | Dd km$^{-1}$ | Δa | log SSY | model equation | SSY MG km$^{-2}$ year$^{-1}$ | total SY MG year$^{-1}$ |
|---|---|---|---|---|---|---|---|
| CASCIANELLA | | | | | | | |
| sub13 | 1.07 | 6.62 | 0.56 | 3.43 | 1.b | 2711.70 | 2893.39 |
| sub12 | 0.12 | 11.23 | 0.50 | 4.07 | 1.b | 11674.56 | 1400.95 |
| | | | | | | subtotal | 4294.33 |
| S. PATRIZIO | | | | | | | |
| sub4 | 0.17 | 7.29 | 0.18 | 3.50 | 1.b | 3145.21 | 534.69 |
| sub5 | 0.20 | 7.33 | 0.38 | 3.53 | 1.b | 3406.17 | 681.23 |
| sub6 | 0.19 | 11.34 | 0.53 | 4.08 | 1.b | 12113.68 | 2301.60 |
| sub7 | 0.44 | 5.65 | 0.00 | 3.43 | 2.a | 2681.65 | 1179.93 |
| sub11 | 0.09 | 7.49 | 0.00 | 3.70 | 2.b | 5066.60 | 455.99 |
| sub14 | 0.03 | 24.04 | 0.00 | 5.19 | 2.b | 155992.77 | 4145.81 |
| | | | | | | subtotal | 9299.25 |
| REILLA | | | | | | | |
| vaccareccia | 2.05 | 3.73 | 0.24 | 2.69 | 1.a | 488.74 | 1001.93 |
| sub8 | 0.68 | 4.29 | 0.00 | 2.97 | 2.a | 933.20 | 634.57 |
| sub15 | 4.92 | 3.36 | 0.52 | 2.60 | 1.a | 395.49 | 1945.81 |
| | | | | | | subtotal | 3582.31 |
| SABBIONE | | | | | | | |
| sub9 | 1.05 | 4.50 | 0.00 | 3.04 | 2.a | 1098.40 | 1153.32 |
| sub10 | 1.15 | 4.87 | 0.38 | 3.08 | 1.a | 1189.28 | 1367.67 |
| sub16 | 4.77 | 3.83 | 0.43 | 2.74 | 1.a | 550.67 | 2626.68 |
| | | | | | | subtotal | 5147.67 |
| Main stream | | | | | | | |
| sub1 | 0.33 | 6.12 | 0.33 | 3.31 | 1.b | 2023.63 | 667.80 |
| sub2 | 0.70 | 4.01 | 0.30 | 2.79 | 1.a | 611.73 | 428.21 |
| sub3 | 0.98 | 2.71 | 0.10 | 2.34 | 1.a | 219.80 | 215.40 |
| | | | | | | subtotal | 1311.41 |
| | | | | | | total SY from sub-catchments | 23634.98 |



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**Table 3.** Sediment yield estimates in secondary (mainly 1st and 2nd order) catchments draining into reservoirs.

| Secondary catchments | Area $km^2$ | Order | Dd $km^{-1}$ | Δa | log SSY | model equation | SSY MG $km^{-2}$ $year^{-1}$ | total SY MG $year^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| REILLA | | | | | | | | |
| res16 | 0.09 | 1 | 3.45 | 0.00 | 2.69 | 2.a | 486.21 | 43.76 |
| res17 | 0.12 | 1 | 3.19 | 0.00 | 2.60 | 2.a | 397.36 | 47.68 |
| res18 | 0.05 | 1 | 6.63 | 0.00 | 3.55 | 2.b | 3540.17 | 177.01 |
| res19 | 0.17 | 2 | 5.00 | 0.00 | 3.21 | 2.a | 1619.20 | 275.26 |
| res20 | 0.32 | 2 | 3.17 | 0.00 | 2.59 | 2.a | 391.24 | 125.20 |
| res21 | 0.47 | 1 | 2.17 | 0.00 | 2.26 | 2.a | 180.04 | 84.62 |
| res25 | 0.12 | 1 | 3.03 | 0.00 | 2.55 | 2.a | 350.96 | 42.11 |
| res27 | 0.07 | 2 | 6.40 | 0.00 | 3.50 | 2.b | 3191.19 | 223.38 |
| res28 | 0.26 | 2 | 1.90 | 0.00 | 2.16 | 2.a | 146.00 | 37.96 |
| | | | | | | | sub-total | 1056.99 |
| SABBIONE | | | | | | | | |
| res10 | 0.08 | 1 | 3.98 | 0.00 | 2.87 | 2.a | 733.63 | 55.05 |
| res11 | 0.29 | 2 | 4.05 | 0.00 | 2.89 | 2.a | 774.59 | 211.24 |
| res12 | 0.36 | 2 | 3.61 | 0.00 | 2.74 | 2.a | 550.50 | 183.36 |
| res13 | 0.59 | 2 | 3.36 | 0.00 | 2.66 | 2.a | 453.41 | 245.24 |
| res15 | 1.31 | 3 | 2.97 | 0.40 | 2.46 | 1.a | 286.80 | 375.70 |
| res22 | 0.21 | 2 | 4.11 | 0.00 | 2.91 | 2.a | 811.52 | 160.62 |
| res23 | 0.48 | 2 | 3.31 | 0.00 | 2.64 | 2.a | 436.15 | 191.57 |
| res24 | 0.15 | 2 | 3.62 | 0.00 | 2.74 | 2.a | 554.79 | 77.03 |
| | | | | | | | sub-total | 1499.81 |
| MAIN STREAM | | | | | | | | |
| res9 (sub3) | 0.98 | 3 | 2.71 | 0.10 | 2.34 | 1.a | 219.80 | 215.40 |
| res1 | 0.59 | 2 | 3.13 | 0.00 | 2.58 | 2.a | 379.28 | 223.78 |
| res2 | 0.28 | 2 | 3.82 | 0.00 | 2.81 | 2.a | 647.96 | 181.43 |
| res3 | 0.12 | 2 | 5.07 | 0.00 | 3.23 | 2.a | 1709.60 | 205.15 |
| res4 | 0.11 | 2 | 4.75 | 0.00 | 3.13 | 2.a | 1333.61 | 146.70 |
| res5 | 0.13 | 2 | 4.63 | 0.00 | 3.08 | 2.a | 1215.01 | 157.95 |
| res6 | 0.09 | 1 | 4.06 | 0.00 | 2.89 | 2.a | 780.63 | 70.26 |
| res8 | 0.18 | 2 | 3.70 | 0.00 | 2.77 | 2.a | 590.33 | 106.26 |
| res14 | 0.17 | 2 | 4.15 | 0.00 | 2.92 | 2.a | 837.11 | 142.31 |
| res26 | 0.13 | 2 | 4.33 | 0.00 | 2.98 | 2.a | 962.62 | 125.14 |
| res30 | 0.11 | 2 | 4.86 | 0.00 | 3.16 | 2.a | 1452.48 | 159.77 |
| res7 | 0.20 | 1 | 3.18 | 0.00 | 2.60 | 2.a | 394.29 | 78.86 |
| res 29 | 0.09 | 1 | 5.09 | 0.00 | 3.24 | 2.a | 1736.35 | 156.27 |
| | | | | | | | sub-total | 1969.27 |
| total area drained by reservoirs | 8.32 | | | | | | TOTAL SY to reservoirs | 4526.07 |
| | | | | | | | SY % trapped in reservoirs | 16% |

**Table 4.** Sediment yield estimates from catchments with badlands (*calanchi*) occurrence.

| catchments with badlands | Area $km^2$ | Order | Dd $km^{-1}$ | Δa | log SSY | model equation | SSY MG $km^{-2}$ $year^{-1}$ | total SY MG $year^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| CASCIANELLA | | | | | | | | |
| Cascianella_calanchi | 1.36 | 4 | 6.03 | 0.56 | 3.32 | 1.b | 2090.75 | 2843.42 |
| sub12 | 0.12 | 3 | 11.23 | 0.50 | 4.07 | 1.b | 11674.56 | 1400.95 |
| Sub-totals | 1.48 | | | | | | | 4244.37 |
| S. PATRIZIO | | | | | | | | |
| S. Patrizio_calanchi | 1.60 | 4 | 7.61 | 1.67 | 3.76 | 1.b | 5730.70 | 9169.12 |
| sub4 | 0.17 | 3 | 7.29 | 0.18 | 3.50 | 1.b | 3145.21 | 534.69 |
| sub5 | 0.20 | 3 | 7.33 | 0.38 | 3.53 | 1.b | 3406.17 | 681.23 |
| sub6 | 0.19 | 3 | 11.34 | 0.53 | 4.08 | 1.b | 12113.68 | 2301.60 |
| sub7 | 0.44 | 3 | 5.65 | 0.00 | 3.43 | 2.a | 2675.33 | 1177.15 |
| sub11 | 0.09 | 3 | 7.49 | 0.00 | 3.70 | 2.b | 5066.60 | 455.99 |
| Sub-totals | 2.69 | | | | | | | 14319.78 |
| REILLA | | | | | | | | |
| Reilla_calanchi | 3.63 | 3 | 3.65 | 0.55 | 2.69 | 1.a | 495.17 | 1797.46 |
| SABBIONE | | | | | | | | |
| Sabbione_calanchi | 2.89 | 3 | 4.15 | 0.49 | 2.85 | 1.a | 710.72 | 2053.98 |
| sub9_calanchi | 0.48 | 3 | 4.65 | 0.00 | 3.09 | 2.a | 1186.47 | 569.51 |
| sub10_calanchi | 0.50 | 3 | 6.64 | 0.45 | 3.42 | 1.b | 2642.22 | 1321.11 |
| Sub-totals | 3.87 | | | | | | | 3944.60 |
| MAIN stream | | | | | | | | |
| Main_calanchi | 1.99 | 3 | 4.69 | 0.32 | 3.01 | 1.a | 1024.63 | 2039.02 |
| sub3 (res 9) | 0.98 | 3 | 2.71 | 0.10 | 2.34 | 1.a | 219.80 | 215.40 |
| Sub-totals | 2.97 | | | | | | | 2254.42 |
| Total badlands surface | 14.64 | | | | | | TOTAL SY from badlands | 26560.63 |
| % of the whole Calvano area | 42% | | | | | | % of the whole Calvano SY | 96% |

**Table 5.** Test-reservoirs sedimentation estimates and comparison with predicted SSYs by model equations.

| Reservoir | Date | Time interval years | Basin | Location | Drainage basin area $km^2$ | Estimated sediment volume $m^3$ | Estimated SSY * $Mg\ km^{-2}\ year^{-1}$ | Predicted SSY by model equations $Mg\ km^{-2}\ year^{-1}$ | Difference % |
|---|---|---|---|---|---|---|---|---|---|
| 20 Pineto | 1959 | 15 | Sabbione | Colle Sciarra | 0.77 | 5000 | 519.48 | 567.86[b] | 9.3% |
| 119 Atri | 1970 | 35 | Calvano | Colle Giudeo | 0.98 | 12500 | 437.32 | 219.80 [a] | –49.7% |
| 147 Atri | 1963 | 25 | Piomba | Acquatina | 0.15 | 15 000 | 4800.00 | 3464.48 [b] | –27.8% |
| 141 Atri | 1971 | 22 | Cerrano | Madonna delle Grazie | 0.15 | 1600 | 581.82 | 925.98 [b] | 59.2% |
| | | | | | | | | average difference = | 36.5% |

* volume-mass conversion by $\gamma_d = 1.2\,\mathrm{Mg\,m^{-3}}$

[a] = Eq. (1a)

[b] = Eq. (2a)

**Table 6.** Sediment yield comparison between south- and northward facing catchments.

| Catchment | | Area km$^2$ | Order | Dd km$^{-1}$ | Δa | log SSY | model equation | SSY MG km$^{-2}$ year$^{-1}$ | total SY MG year$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| southward catchments | | | | | | | | | |
| (main) | sub2 | 0.43 | 3 | 4.04 | 0.30 | 2.80 | 1.a | 625.67 | 269.04 |
| | res1 | 0.59 | 2 | 3.13 | 0.00 | 2.58 | 2.a | 379.28 | 223.78 |
| | res2 | 0.28 | 2 | 3.82 | 0.00 | 2.81 | 2.a | 647.96 | 181.43 |
| | res3 | 0.12 | 2 | 5.07 | 0.00 | 3.23 | 2.a | 1709.60 | 205.15 |
| | res4 | 0.11 | 2 | 4.75 | 0.00 | 3.13 | 2.a | 1333.61 | 146.70 |
| | res5 | 0.13 | 2 | 4.63 | 0.00 | 3.08 | 2.a | 1215.01 | 157.95 |
| | res26 | 0.13 | 2 | 4.33 | 0.00 | 2.98 | 2.a | 962.62 | 125.14 |
| | res30 | 0.11 | 2 | 4.86 | 0.00 | 3.16 | 2.a | 1452.48 | 159.77 |
| | res29 | 0.09 | 1 | 5.09 | 0.00 | 3.24 | 2.a | 1736.35 | 156.27 |
| (Reilla) | res27 | 0.07 | 2 | 6.40 | 0.00 | 3.50 | 2.b | 3191.19 | 223.38 |
| | | | | | | | average | 1325.38 | 184.86 |
| northward catchments | | | | | | | | | |
| (main) | (res9) sub3 | 0.98 | 3 | 2.71 | 0.10 | 2.34 | 1.a | 219.80 | 215.40 |
| | res8 | 0.18 | 2 | 3.70 | 0.00 | 2.77 | 2.a | 590.33 | 106.26 |
| | res7 | 0.2 | 1 | 3.18 | 0.00 | 2.60 | 2.a | 394.29 | 78.86 |
| (Reilla) | res16 | 0.09 | 1 | 3.45 | 0.00 | 2.69 | 2.a | 486.21 | 43.76 |
| | res21 | 0.47 | 1 | 2.17 | 0.00 | 2.26 | 2.a | 180.04 | 84.62 |
| | res20 | 0.32 | 2 | 3.17 | 0.00 | 2.59 | 2.a | 391.24 | 125.20 |
| | res28 | 0.26 | 2 | 1.90 | 0.00 | 2.16 | 2.a | 146.00 | 37.96 |
| (Sabbione) | res10 | 0.08 | 1 | 3.98 | 0.00 | 2.87 | 2.a | 733.63 | 58.69 |
| | res23 | 0.48 | 2 | 3.31 | 0.00 | 2.64 | 2.a | 436.15 | 209.35 |
| | | | | | | | average | 397.52 | 106.68 |

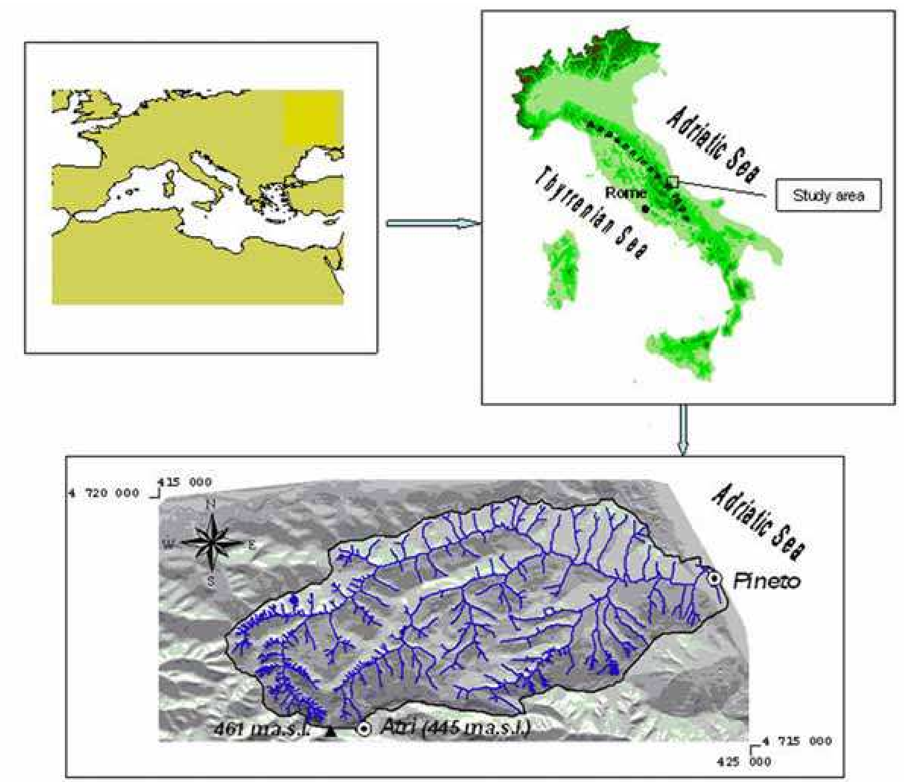


**Fig. 1.** Geographic location of the Calvano watershed. Projection East U.T.M. 33 European Datum 1950.

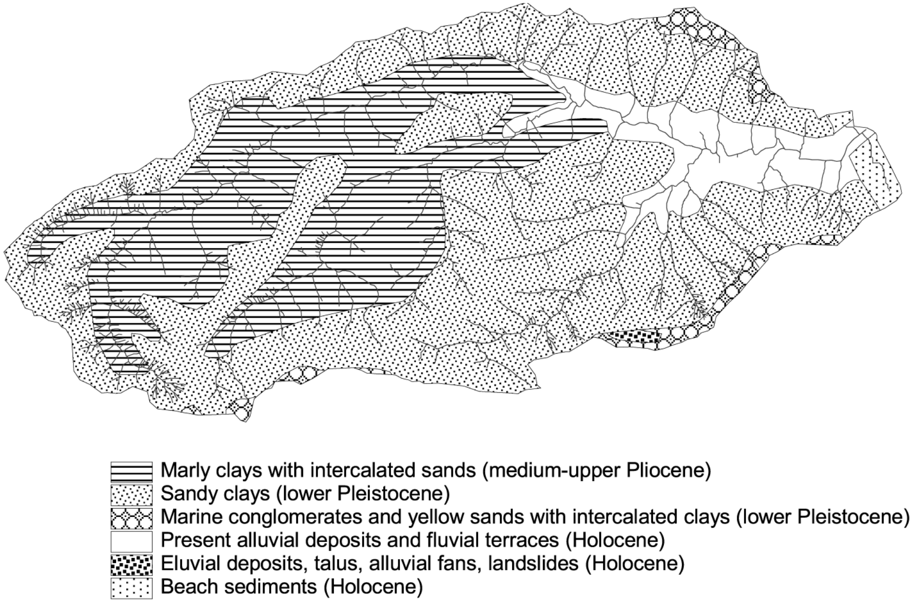


**Fig. 2.** Geo-lithological scheme.



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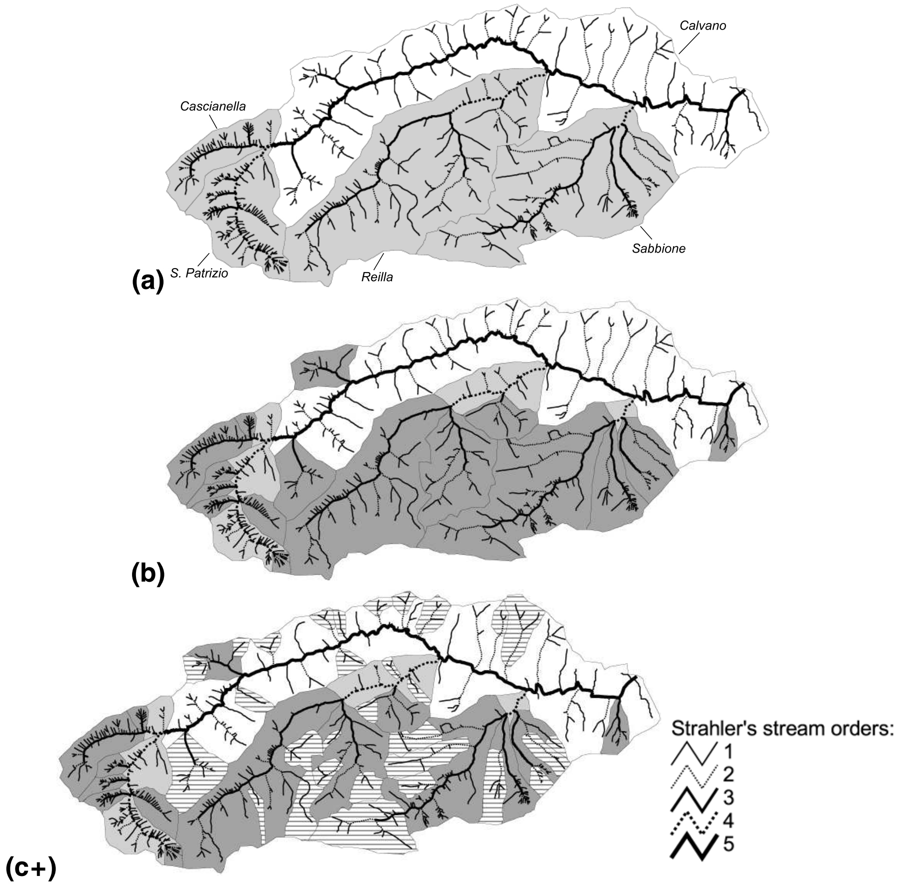


**Fig. 3.** Different patterns of the Calvano watershed subdivision: **(a)** 4th order partial catchments draining into the main stream; **(b)** previous plus 3rd order sub- catchments; **(c)** previous plus 2nd and 1st order secondary catchments draining into hill-reservoirs.



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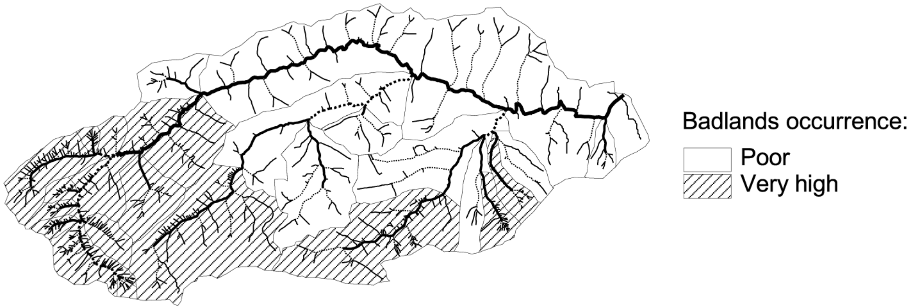


**Fig. 4.** Location of catchments affected by badlands.



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